

# Gazification of coal dust particles in the blast furnace tuyere apparatus

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**Abstract.** The mathematical statement of the problem on gasification of coal dust particles in the blast-furnace tuyere apparatus is given, which includes the motion equation of a variable mass particle, heat equation of a particle and the heat-balance equation of the blast flow. The results of calculations are obtained by using mathematical software packages (Mathcad, Maple). Relatively weak effect of the volatiles combustion process on the thermal state of the tuyere zone is shown.

## 1. Introduction

At the present time, the interest in the use of pulverized coal fuel in the blast furnace process is rising [1-3]. Typically, the injection of pulverized coal into the blast furnace is carried out at a distance of 1 m from the tuyere outlet section [4, 5]. Prior to getting into the tuyere cavity in the coal dust particles (CD) the processes of heat- and mass-transfer take place, that leads to a change in the boundary conditions of mathematical (numerical) model of the blast furnace combustion zone (CZ) [6, 7]. In general, simulation of combustion processes in CZ is rather complicated due to the high turbulence of the recycle gas flows, spatial heterogeneity of CZ walls temperatures, temperature and composition of the recycle gas, constant lowering of coke layer, which leads to entry of coke particles into the CZ zone.

The degree of CD burn-out inside the tuyere (if the coal is counter-injected to the blast flow) and inside CZ determines the temperature of CZ, and the unburned material, which, like the ash (coke residue), collides with the CZ walls, is the potential cause of problems arising because of the low gas permeability.

Accounting for a change in the boundary conditions of mathematical model of blast furnace CZ is connected with the solution of the problem.

## 2. Calculation of the motion and heat of CD particles

In some section  $x = 0$ , CD particles enter into blast flow in the amount  $W$ , g/m<sup>3</sup> of the blast. We need to determine the change in particles velocity and their temperature, amount of volatile yield, gas (blast) temperature along the length of the tuyere pipe with diameter  $d_t$ .

According to the basic provisions of the theory of coals combustion [8] the chemical reactions of carbon with oxidants start when the greater part of the volatiles yields from the particles. CD particles, incoming into the blast flow, interact with the blast, accelerate and get heated. During this process volatiles are released and burned. The mass of CD particles decreases in the process of their



movement and heating. The particles are heated by gas, mainly by convection, since carbon monoxide  $\text{CO}_2$  in the blast is practically absent, and content of  $\text{H}_2\text{O}$  does not exceed 2.5%. In principle, the heating of particles is possible by radiation from the walls of the tube, for its accounting it is necessary to know the change in the temperature of pipe walls along the blast flow, but it will greatly complicate the task.

The mathematical statement of the problem includes the motion equation of a variable mass particle, heat equation of a particle and the heat-balance equation of the blast flow. Each of these equations becomes more complicated as the described phenomena are accompanied by the release and burning (oxidation) of CD volatiles.

According to the 2nd Newton's law [9] the change in momentum equals to the impulse of effective forces. In the one-dimensional representation the only effective force is the force of aerodynamic resistance. For a variable mass particle the dependence is valid [6, 9]

$$\frac{d(m_p v_p)}{d\tau} = \frac{1}{2} C_D \rho_g |v_g - v_p| (v_g - v_p) \frac{\pi d_p^2}{4}, \quad (1)$$

where  $m_p$  and  $d_p$  – weight and size of a particle, kg and mm;  $v_g$  and  $v_p$  – flow rates of blast and CD particles, m/s;  $C_D$  – drag coefficient;  $\rho_g$  – blast density,  $\text{kg/m}^3$ .

For CD particles of typical sizes the drag coefficient can be determined from relations [6, 9, 10-12]

$$C_D = \begin{cases} \frac{24}{\text{Re}_p} (1 + 0.15 \text{Re}_p^{0.687}) & \text{if } \text{Re}_p < 1000; \\ 0.44 & \text{if } \text{Re}_p \geq 1000; \end{cases}$$

here  $\text{Re}_p$  – Reynolds number of a CD particle

$$\text{Re}_p = \frac{\rho_g |v_g - v_p| d_p}{\mu_g}, \quad \mu_g - \text{dynamic viscosity of blast, Pa}\cdot\text{s}.$$

Left side of the equation (1) can be written as  $\frac{d(m_p v_p)}{d\tau} = m_p \frac{dv_p}{d\tau} + v_p \frac{dm_p}{d\tau}$ .

The coal particle consists of coke residue, weight of which is unchanged at this stage, and volatiles. The initial amount of volatiles  $V_{i0}$  kg is determined by the relation [6, 8]  $V_{i0} = 0.01 m_{p0} V_i$ , here  $m_{p0}$  is the initial mass of a particle;  $V_i$  – amount of volatiles in the initial coal, % (by weight). The current mass of a dust particle  $m_p(\tau)$  can be represented as follows:

$$m_p(\tau) = m_{p0} [1 - 0.01 V_{i0}(\tau)] = m_{p0} \left[ 1 - 0.01 V_i \frac{V_{i0}}{V_i} \right] = m_{p0} [1 - 0.01 V_i \delta(\tau)],$$

where  $V_{i0}(\tau)$  – current amount of volatiles;  $\delta(\tau)$  – fraction of the released volatiles. According to the two-stage scheme [8] of volatiles release the equation is valid

$$\delta(\tau) = \frac{V_{i0}(\tau)}{V_i} = C_{01} \left[ 1 - \exp \left( - \int_0^\tau k_{1v} d\tau \right) \right] + C_{02} \left[ 1 - \exp \left( - \int_0^\tau k_{2v} d\tau \right) \right],$$

where  $C_{01}$  and  $C_{02}$  – empirical coefficients (fractions);  $k_{1v}$  and  $k_{2v}$  – rate constant rate of reaction of volatile release at the stage of release of capillary-bound volatiles and the stage of destruction of chemical bonds,  $s^{-1}$ . Under this scheme the rate of change in the weight of a coal particle is determined by the dependence

$$\begin{aligned} \frac{dm_p}{d\tau} &= -0.01V_l \frac{d\delta(\tau)}{d\tau} = -0.01V_l \varphi(\tau) = \\ &= -0.01V_l \left[ C_{01}k_{1v} \exp\left(-\int_0^\tau k_{1v} d\tau\right) + C_{02}k_{2v} \exp\left(-\int_0^\tau k_{2v} d\tau\right) \right]. \end{aligned}$$

Here  $\varphi(\tau)$  – effective reaction rate of volatile release.

For the use of Runge-Kutta method [13] the equation (1) needs to be written as  $dv_p/d\tau = f(\dots)$ , and it is more convenient to replace the time derivative by the coordinate derivative  $d\tau = dx/v_p$ . The equation (1) in its final form will be

$$\frac{dv_p}{dx} = \frac{0.01V_l \varphi(\tau)}{1 - 0.01V_l \delta(\tau)} + \frac{\left[ 1 + 0.15 \left( \frac{\rho_g |v_g - v_p| d_p}{\mu_g} \right)^{0.687} \right] (v_g - v_p)}{\tau_p v_p [1 - 0.01V_l \delta(\tau)]}, \quad (2)$$

where  $\tau_p = \frac{\rho_p d_p^2}{18\mu_g}$  – time of particle relaxation.

Heat equation of a CD particle in the case of convective heat-transfer has is [6, 7, 13]

$$c_p m_p \frac{dt_p}{d\tau} = \alpha (t_g - t_p) \pi d_p^2,$$

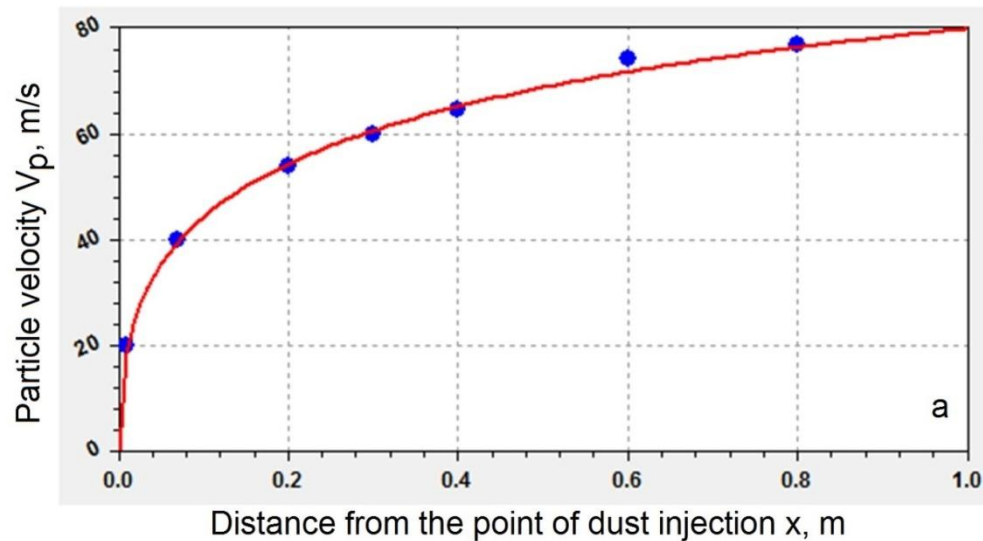
where  $c_p$  and  $c_g$  – specific heat capacity of a particle and gas, J/(kg·K);  $t_p$  and  $t_g$  – particle temperatures and flow of blast, °C;  $\alpha$  – heat-transfer coefficient, W/(m<sup>2</sup>·K). If we use the expression of Nusselt number [6, 7, 13]  $Nu = \alpha d_p / \lambda_g = 2 + 0.634 Re^{1/2} Pr^{1/3}$ , where  $\lambda_g$  is the coefficient of thermal conductivity, W/(m·K), to determine the heat-transfer coefficient, the following dependence will be obtained

$$\frac{dt_p}{dx} = \frac{6\lambda_g \left[ 2 + 0.634 \left( \frac{\rho_g |v_g - v_p| d_p}{\mu_g} \right)^{0.5} \left( \frac{\mu_g c_g}{\lambda_g} \right)^{0.33} \right] (t_g - t_p)}{c_p v_p d_p^2 [1 - 0.01V_l \delta(\tau)]}. \quad (3)$$

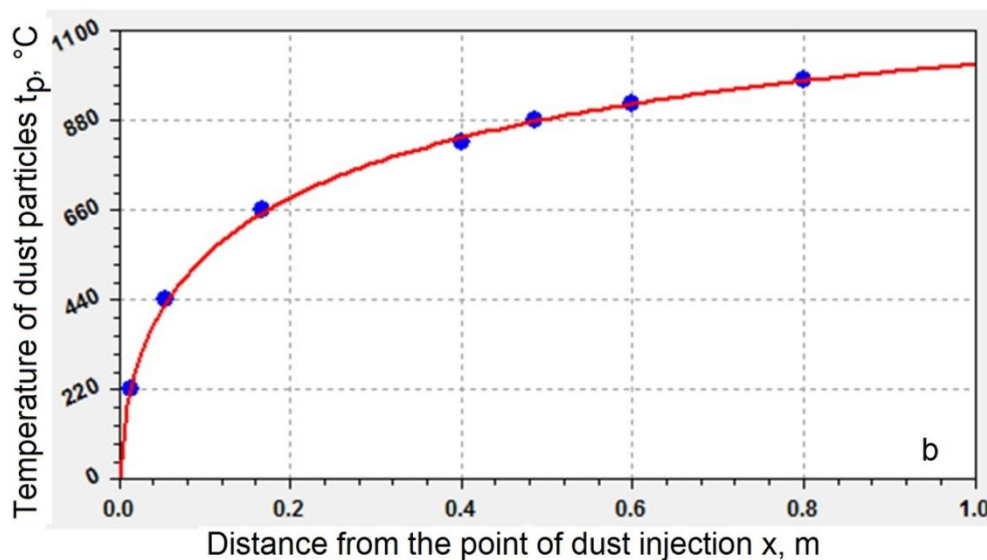
Equations (2) and (3) are sufficient to answer the question concerning the change in the velocity of a CD particle and its temperature. Below in Figure 1 the results of calculations are given for the particular case of  $W = 2.5$  g/m<sup>3</sup>,  $V_g = 1.27$  m<sup>3</sup>/s (the initial gas flow rate in the CZ),  $d_p = 0.15$  mm  $d_t = 160$  mm. In Figure 1, a the change in the velocity of motion of a CD particle is shown as the distance from the place of its entry into the blast increases. The initial velocity of the particle is 5 m/s. The particle under the action of the blast flow rather quickly gains velocity. Relatively quickly rises the temperature of a CD particle (Figure 1, b).

### 3. Calculation of the processes of volatiles release and blast heat balance

While forming the heat equation it is necessary to take into account all CD particles contained in 1 m<sup>3</sup> of blast. It is required to determine the amount of heat released during the volatile combustion, which depends on the coefficient of Bunte [6, 7, 8]. Bunte coefficient is determined by  $Bu = 2.37 (H_r - 0.125O_r)/C_r$ , where  $H_r$ ,  $O_r$  and  $C_r$ — content (by weight) of carbon, hydrogen and oxygen in the coal working mass. Amount  $Q_v$  of heat released during the volatile oxidation is  $Q_v = 10^6 (105 Bu - 33)$ , J/kg of volatiles.



a



b

**Figure 1.** Change in the motion velocity of a CD particle (a) and its temperature (b) as the distance from the injection point to the blast flow increases.

1 m<sup>3</sup> of blast contains  $0.001W$  kg of coal particles with  $0.01V_r - 0.001W$  kg of volatiles. The total surface area  $F$  of CD particles in 1 m<sup>3</sup> of blast is  $F = 0.001W \frac{6}{\rho_p d_p}$ , m<sup>2</sup>/m<sup>3</sup> of blast.

Thus, the following dependence can be written as:

$$\frac{dt_g}{dx} = \frac{\lambda_g F \left[ 2 + 0.634 \left( \frac{\rho_g |v_g - v_p| d_p}{\mu_g} \right)^{0.5} \left( \frac{\mu_g c_g}{\lambda_g} \right)^{0.33} \right] (t_p - t_g)}{C_{vg} d_p v_p} + \frac{0.001W \cdot 0.01V_l Q_v \varphi(x)}{C_{vg} v_p},$$

where  $C_{vg}$  – the heat capacity per unit volume of gas, J/(m<sup>3</sup>·K);

$$\varphi(x) = C_{01} k_{1v} \exp\left(-\int_0^x \frac{k_{1v}}{v_p} dx\right) + C_{02} k_{2v} \exp\left(-\int_0^x \frac{k_{2v}}{v_p} dx\right), s^{-1}$$

To “launch” the process of volatiles release it is necessary to overcome an energy barrier. As an example for the calculation the coal with the following composition was chosen: 74.30 %  $C_r$ , 4.82 %  $H_r$ , 8.01 %  $O_r$ ; coal ash was 7.1 %, 38.7 % volatiles content. The rate constants for the reactions of volatiles release are determined by the relations [6, 8, 14]

$$k_{1v} = 1.34 \cdot 10^5 \exp\left[\frac{74000}{8.3143(t_p + 273)}\right]; \quad k_{2v} = 1.46 \cdot 10^{13} \exp\left[\frac{251000}{8.3143(t_p + 273)}\right].$$

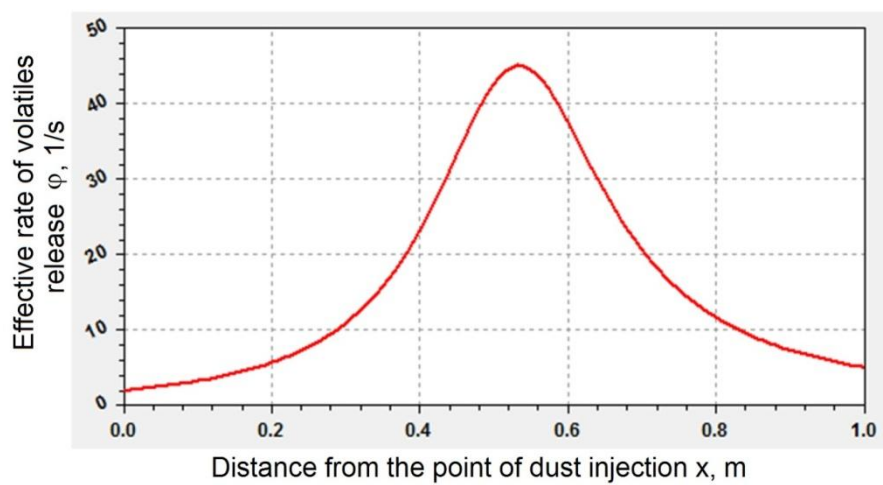
The values of coefficients  $C_{01}$  and  $C_{02}$  are 0.33 and 0.67 respectively. The effective rate  $\varphi(x)$  of the reaction of volatiles release is maximal at the stage of a sharp increase in the particle temperature (Figure 2).

At a distance of 0.3 m the volatiles practically are not released (Figure 3, a). Temperature of 770 °C in this case can be considered as the temperature of the beginning of volatile release for the coal grade under consideration. High rate of volatiles release should be noted – more than 96 % of volatiles contained in the coal are released at a distance of 1 m from the point of injection of CD particles into the flow.

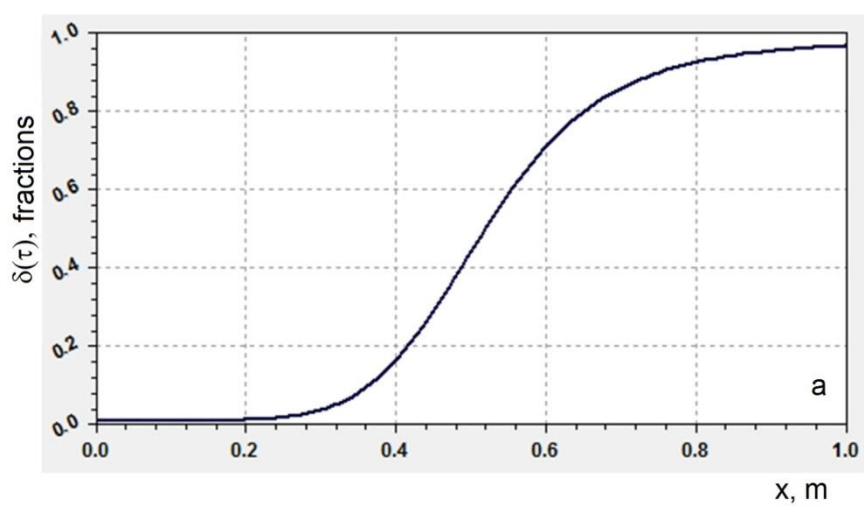
In Figure 3, b the change in temperature of the gas flow, when it interacts with the CD particles, is shown. In this example, the pulverized coal is introduced cold into the blast, thus, initially the gas temperature slightly decreases (less than 1 °C, which practically cannot be seen in the figure). However, during the volatiles combustion (within 0.35 m) the gas temperature is recovered and then goes up at 7.8 °C.

#### 4. Conclusions

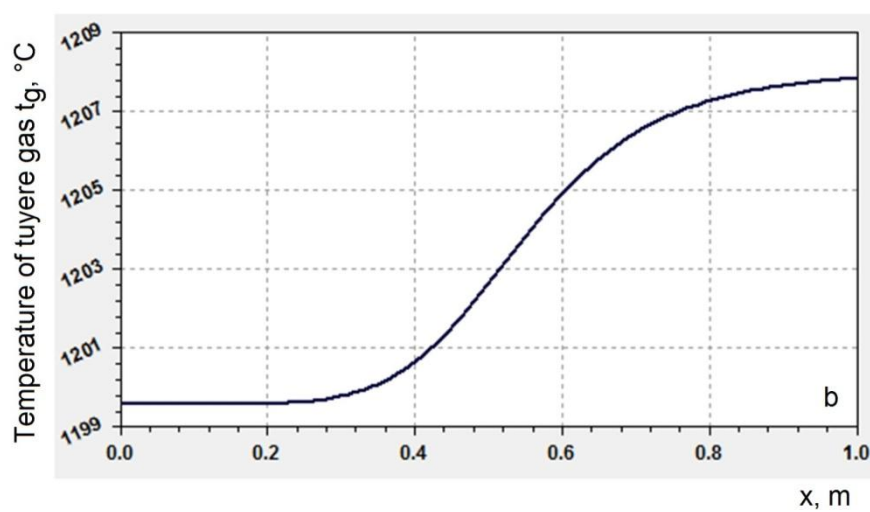
The given in this work results characterizes only the first stage in the development of heat- and mass-transfer process during the pulverized coal injection – volatiles release; calculation is valid for the chosen CD consumption. There is a relatively weak influence of the volatiles combustion on the thermal state of the tuyere zone. Thus, with the increase in CD consumption by 60 % (up to 4 g/m<sup>3</sup>) the gas temperature at the end of the particle's trajectory goes up to 1212.4 °C (only 4.6 °C).



**Figure 2.** Influence of the path travelled by the particle on the effective reaction rate of volatiles release.



a



b

**Figure 3.** Change in the fraction of released volatiles (a) and the temperature of tuyere gases (b) as distance from the enjection point of coal dust particles into the blast flow increases.

## 5. References

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